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GENERATION OF DARK PULSES IN A BISMUTH TELLURITE BASED MODE-LOCKED ERBIUM-DOPED FIBER LASER

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We report on the formation of dark pulses in a highly nonlinear fiber laser passively mode-locked by a Bistmuth Tellurite (Bi_2Te_3) based SA. The SA was fabricated by embedding Bi_2Te_3 powder into polyvinyl alcohol (PVA) film by a solution casting technique. By inserting the SA into an EDFL cavity, stable mode-locked operation was achieved at 1592.68 nm with the maximum pulse energy up to 2.38 nJ by adjusting polarization controller. The laser operated at pulse repetition frequency of 1.0 MHz with a pulse width of 215 ns. These results suggested that Bi_2Te_3 could be developed as an effective SA for mode-locked dark pulses generation in a highly nonlinear cavity.

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Keywords: Dark pulses, Bismuth Telluride, passive saturable absorber, Mode-locking

1. Introduction

In recent decades, mode-locked fiber lasers have been extensively investigated for the generation of ultrashort pulses [1–3]. The mode-mode-locked laser can be realized through the synchronizion of the phases of all oscillating longitudinal modes in the laser cavity. It can produce a narrow pulses and the pulse width generated is determined by amount of locked phases, which is depended on the laser gain bandwidth. The mode-locked laser pulses are nowadays widely applied in many advanced fields such as in industrial material processing, remote sensing, medical treatment, spectroscopy, communication and scientific researches [4-7]. They can be obtained by employing a passive saturable absorber (SA) device inside a fiber laser cavity. Up to date, a wide variety of SAs have been reported for mode-locked pulses generation such as semiconductor saturable absorber mirrors (SESAMs), single-wall carbon nanotubes (SWCNTs) [8-9]. SESAMs are widely used due to their flexibility and robustness, but they have the narrow operating bandwidth and are still quite costly for purposes of mass production. SWCNTs are not efficient since the absorption wavelength is depend on the nanotube diameter.

The emergence of two-dimensional(2D) nanomaterials effectively solve the problems above due to their unique optical properties and Pauli blocking induced saturable absorption. Recently, 2D nanomaterials such as graphene, black phosphorus, transition metal dichalcoganides (TMDs), topological insulators (TI) have fascinated many interests for SA applications [10-12]. Among these excellent 2D materials, TIs have attracted much research interest due to their large modulation depth with efficient saturable absorption property [13].

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Besides, the bright pulses, mode-locked fiber lasers can also emit darl pulses. Here dark pulses are referred to as a train of intensity dips in the intensity of a CW background of the laser emission. The transmission of dark pulses through a single mode fiber (SMF) was firstly reported by Emplit et al in 1978 [14]. Recently, dark pulses generations have been extensively investigated in both Q-switched and mode-locked fiber lasers [15-17]. Compared with the conventional bright pulses, dark pulses have advantages in terms of its stability in noisy environments and they are less influenced by stimulated Raman scattering [18]. To date, many works on dark pulses lasers were reported. For instance, in 2014, Tiu et al reported a dark pulses generation in a normal dispersion fiber laser cavity using the nonlinear polarization rotation (NPR) method [19]. The generation of dark pulses in a dispersion-managed fiber ring laser was then reported by Ge et al. [20]. In 2016, Liu et al reported the generation of dark solitons in erbium-doped fiber laser (EDFL) cavity using Tungsten disulfide as SA [21]. In addition, new types of dark pulses based on polarization domain wall and dual-wavelength domain wall were also theoretically predicted and then experimentally demonstrated in fiber laser cavities [22-23]

In this letter, we experimentally demonstrate the generation of dark pulses in a mode-locked fiber laser based on Zirconia Yttria Erbium-doped fiber (Zr-EDF) gain medium and Bistmuth Tellurite (Bi_2Te_3) SA. By adjusting the polarization controllers and changing the 980 nm pump power, switching between the bright pulse and dark pulse can be easily realized. The dark pulses was formed mainly by an effect of saturable absorption and high nonlinearity.

2. Experimental arrangement

In the experiment, Bi_2Te_3 powder (Sigma Aldrich) with molecular weight of 800.76g/mol was used as the SA material while the water-soluble synthetic polymer, PVA was prepared in the form of thin film as a host material. PVA thin film was selected as it has high strength, high flexibility and low optical absorption at 1550 nm wavelength region. The host polymer was prepared by dissolving 1 g of PVA powder (Sigma Aldrich) into 120ml de-ionized (DI) water with the aid of a magnetic stirrer at room temperature. The SA film was prepared by mixing 25 mg of Bi_2Te_3 with 5 ml of the prepared PVA solution. The mixture was stirred for about three hours using a magnetic stirrer. The thoroughly mixed Bi_2Te_3 PVA solution was then placed in an ultrasonic bath for about an hour to fully bind the Bi_2Te_3 powder with the PVA. After that, the Bi_2Te_3 PVA solution was carefully poured onto a petri dish and was left to dry at room temperature for about 48 hours to to form Bi_2Te_3-PVA composite film. A tiny piece of the film was attached to the end of a fiber ferrule for fiber laser cavity integration. Another ferrule was then used to sandwich the film via a fiber adaptor. A small amount of index matching gel was applied at the connection to minimize parasitic reflections. The absorption loss of the film was measured to be about 3.5 dB at 1550 nm region.

The SA device was then integrated into a fiber laser cavity as shown in Fig. 1. The laser cavity was about 211 m long, consisting of a 2m long of Zr-EDF, an isolator, the prepared SA device, a polarization controllers (PC), a 200 m long standard single mode fiber (SMF), an 90:10 output coupler and a wavelength division multiplexer (WDM). The Zr-EDF was fabricated in a ternary glass host, zirconia–yttria–aluminum (Zr–Y–Al) co-doped silica glass. The fiber has a pump absorption rate of about 14.5 dB/m at 980 nm. It was forward pumped by a 980-nm laser diode via the WDM. The isolator was used to ensure unidirectional propagation of light inside the cavity to prevent any detrimental effects. The additional SMF was added into the cavity to tailor the dispersion characteristic and nonlinearity of the cavity for mode-locking operation. The output laser was coupler out from 10% port of the 90:10 output coupler while 90% of the oscillating light was retained inside the cavity. The output spectrum of the mode-locked laser was measured by an optical spectrum analyzer (OSA) with 0.05 nm spectral resolution. A 500-MHz digital oscilloscope was utilized to analyze the output pulse train via a photodetector. The average output power was measured by an optical power meter. 7.8 GHz Radio Frequency (RF) spectrum analyzer was used to obtain the RF spectrum.

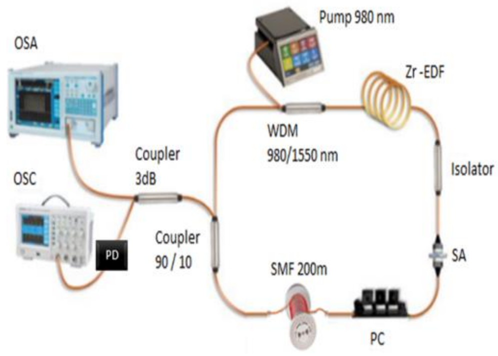

Fig. 1. A schematic of the mode-locked EDFL cavity with Zr-EDF gain medium and Bi_2Te_3 SA.

3. Results and discussion

The dependence of output power and pulse energy on the pump power for the mode-locked fiber laser was firstly investigated, as shown in Fig. 2. As shown in the figure, the threshold for oscillation and slope efficiency were found to be 91 mW and 2.37%, respectively. The threshold pump power was relatively high due to the incorporation of the additional SMF in the cavity which increases the cavity loss. The fiber laser ran into mode-locking regime at the pump power of 91 mW. By carefully adjusting the PC, stable dark pulse could be observed. However, the pulse trains collapsed as the pump power was increased above 121 mW. At pump power of 121 mW, the maximum average output power and pulse energy were obtained at 2.6 mW and 2.38 nJ, respectively.

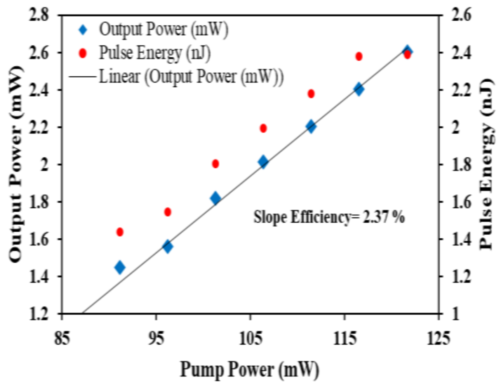

Fig. 2. Average output power and pulse energy as a function of pump power

Fig. 3 shows the output spectrum of the fiber laser with and without the Bi_2Te_3 based SA. The output optical spectra shows a multi-wavelength emission with line intervals of 0.3 nm and 0.8 nm, with and without SA, respectively. The multi-wavelength emission is most probably due to the high nonlinearity effect of Zr-EDF. The laser operations centred at 1592.68 nm and 1602.12 nm for mode-locked pulses and CW, respectively. The operating wavelength has shifted to a shorter wavelength with the incorporation of SA in the cavity. This is attributed to the insertion loss of the SA, which forces the laser operation to shift to a shorter wavelength region, which has a higher gain to compensate for the loss.

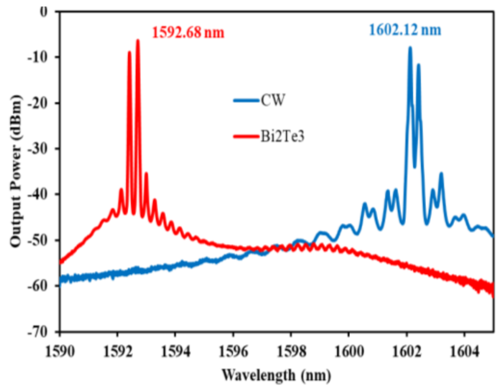

Fig. 3. Optical spectra of the dark pulse and CW lasers from the EDFL cavity.

Fig. 4 shows the oscilloscope trace of the laser emission, which indicates that the laser emits stable dark, as the phenomenon reported in [24]. It has pulse to pulse interval of 1 μs correspond to repetition rate of 1 MHz. The repetition rate matches with the cavity roundtrip time. The dark pulse is about 215 ns wide. To investigate the stability of the output pulse, the RF spectrum was measured as depicted in Fig. 5. The signal-to-noise is ~64 dB, indicating the dark-bright pulse pair is stable. To eliminate the possibility of mode-locked laser caused by the self-pulsing effect, the fiber laser characteristics without Bi_2Te_3 SA were also investigated. Only CW operation was found, without any sign of mode-locking operation with the angle of PC tuned in the total range of 360° or the pump power increased from the oscillation threshold (91 mW) to the maximum (200 mW). The phenomenon verified the vital function of SA in forming the dark pulses in highly nonlinear cavity. The saturable absorption and nonlinear effect are attributed to the generation of the dark pulses.

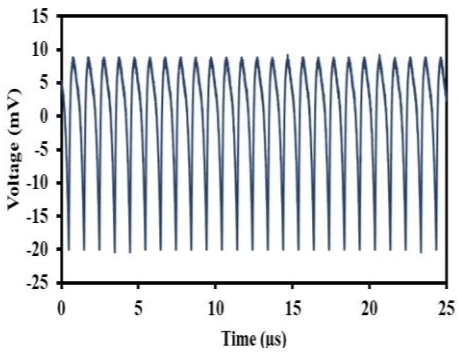

Fig. 4. Typical pulse train of the dark pulse laser.

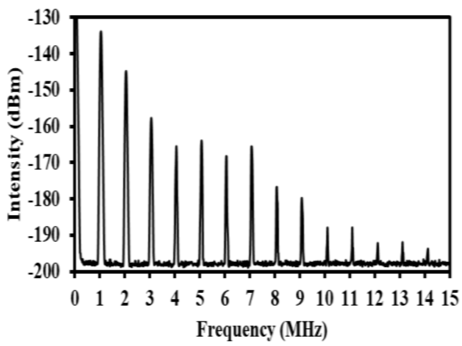

Fig. 5. RF spectrum of the dark pulse laser.

5. Conclusions

A stable dark pulse laser was successfully demonstrated using the Bi_2Te_3 based SA in highly nonlinear EDFL cavity. The SA film used in our experiment was prepared by embedding Bi_2Te_3 into PVA by a solution casting approach. It was integrated into the fiber ring cavity with Zr-EDF gain medium to generate a dark pulse laser with multi-wavelength emission centred at 1592.68 nm.

The dark pulse was generated by the effect of saturable absorption and high nonlinearity. The dark pulse laser operated at threshold pump power of 91 mW, repetition rate of 1.0 MHz and pulse width of 215 ns. The fundamental frequency of the RF spectrum shows a SNR of 64 dB, indicating the excellent stability of the pulses.

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